Deep Underground Cryostat for a LArTPC

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I. Deep underground physics experiments

A number Particle Physics and Astrophysics experiments can take advantage of a facility like the Deep Underground Science and Engineering Laboratory (DUSEL) currently in the site selection stage[1]. In these experiments only neutrinos and very high energy muons can generate background events that lessen their sensitivity. One class of experiment searches for proton decay or cosmic neutrinos sources and, with an appropriately designed and aimed neutrino beam, investigates CP-violation in neutrino oscillations.

II. Liquid Argon Time Projection Chamber

A Liquid Argon Time Projection Chamber (LArTPC) is capable of extraordinary precision in neutrino and proton decay studies. The ICARUS collaboration has pioneered this technology by building a series of detectors increasing in size and performance culminating in the T600 detector (600 tons of liquid Argon at 87 Kelvin) being installed in Hall-B of the Gran Sasso Laboratory[2]. The halls at the Gran Sasso have the approximate shape of a horizontal cylinder 10 m in radius and 100 m long. The T600, two 4 m x 4 m, and 20 m long cryostats constructed from LN2 cooled aluminum panels and the associated cyrogenic systems easily fit into this hall. However, to address CP-violation in neutrino oscillations single detectors employing a mass of least 30 kilotons will be required. If the mixing angle conspires against easy observation of electron neutrino appearance, detectors many times this size may be required. Scaling the construction methods of the T600 detector to a such a massive detector unfortunately also leads to massive costs.

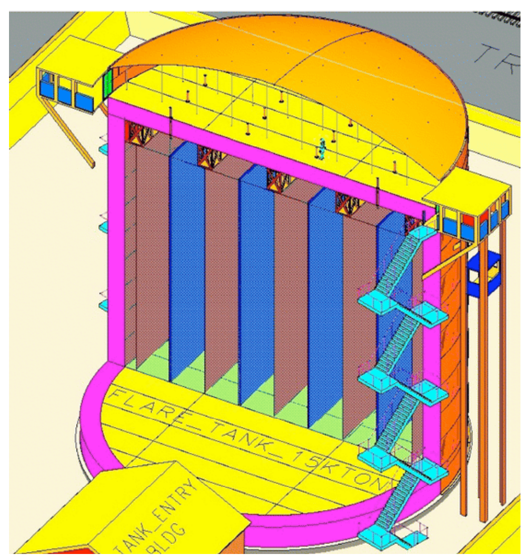

Fig. 1 Section of a 15kT LarTPC, showing the wires planes and the insulation (violet) sandwiched between an inner and outer tank.

To address this difficulty it has been proposed that the cryostat of a LArTPC be built in a upright cylindrical tank similar to those used to store Liquid Natural Gas (LNG) at a temperature of 110 Kelvin. These tanks are constructed with an inner vessel of 9% nickel (or stainless) steel with an open top that is loosely closed with a thermally insulating plug. An outer tank of carbon steel protects the inner tank from the elements, and creates a gas tight volume. A layer of insulation usually Perlite (expanded volcanic glass) fills most of the space between the walls of the two tanks. Key to the design is the self supporting nature of the thick walls of the inner tank. The insulation is not attached to the walls to allow the inner tank to shrink as it cools. Therefore, the insulation cannot not provide any mechanical strength for the inner tank. The largest LNG tanks are cylinders 40 meters high with an 80 meter diameter. If an appropriate tank this large were filled with Argon it would hold over 200 kTon of liquid.

A recent R&D proposal[3] lays out the plans to build a series of these tanks and detectors culminating in the 15 kTon detector, as shown in Figure 1, with an inner tank 19 m high, 26 m in diameter. The tank design for an LArTPC modifies the standard LNG tank to maintain ultra-pure Argon in a completely sealed inner tank with wire planes strung between its roof and floor. Signal towers that start just above the liquid level allow cables to pass through the insulation to a gas tight feed-through.

The height of a LArTPC tank may be limited because capacitance (and therefore the electronic noise) of the readout increases linearly with the wire length. Thus a short and squat cylinder is preferable to one that is tall and narrow. Underground, this implies excavation of a cavern with large spans, which is the type of cavern mine engineers try to avoid. As discussed in the Homestake reference design study[4] mine engineers prefer a horizontal cylinder, perhaps modified into the "rural mailbox" shape, or a tall and narrow vertical cylinder. Fortunately, a new class cryogenic tank has been developed in the last few years which has the shape flexibility to conform to cavern shapes preferred by mine engineers.

III. LNG tanker design

Early generation of ships carried compressed natural gas (CNG) in a large number of high pressure gas (250 bar) cylinders. The gas was subsequently liquefied for storage on land. Later, ships were developed to carry LNG in low pressure spherical tanks of nickel-steel or aluminum. A typical LNG ship of this type carries 4 spheres each with a volume of ~35,000 m^3 . Only recently have LNG tankers been built to carry the liquid in tanks that conform to the shape of the hull.

The breakthrough in design[5] is made possible by the use of Invar, a high (36%) nickel content steel that remains malleable at cryogenic temperatures and has a nearly zero coefficient of expansion. The insulation can now be glued between the inner Invar tank(s) and the outer mild steel hull structure, and can provide the mechanical strength to support the weight and side pressure of the liquid. Invar, however, is very expensive and therefore must be as thin as possible. The basic structure, as shown in Figure 2, uses two "membranes" of 0.7 mm Invar separated from each other and from the vessel's hull by plywood boxes filled with perlite insulation,. The two layers of Invar and two layers of insulation have a total thickness of only 0.53 m, that limits the "boil-off" to 0.15% per day, sufficient for the 10-15 day sail

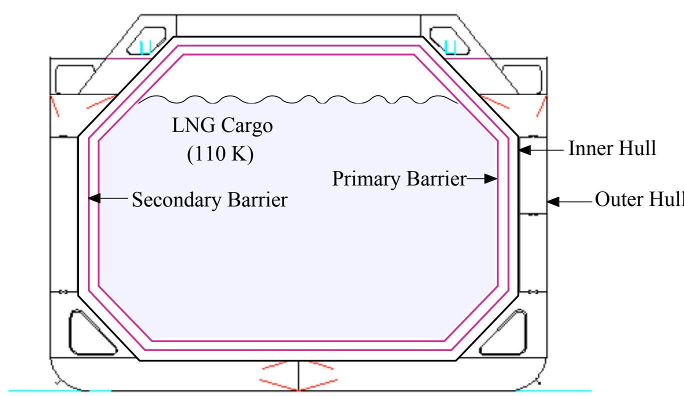

Fig. 2 Membrane LNG tanker design fundamentals

from the gas well to a port. For long term storage, thicker insulation would reduce the refrigeration needs to achieve a much lower boil-off rate.

A number of ships have been built with this initial design[5,6]. The last stage in the construction is welding of the inner Invar membrane as shown in Figure 3. Once each sealed compartment is completed, the welds are inspected and leak tested by pressurizing the insulation layer with 20% helium and scanning a helium leak detector over all the welds.

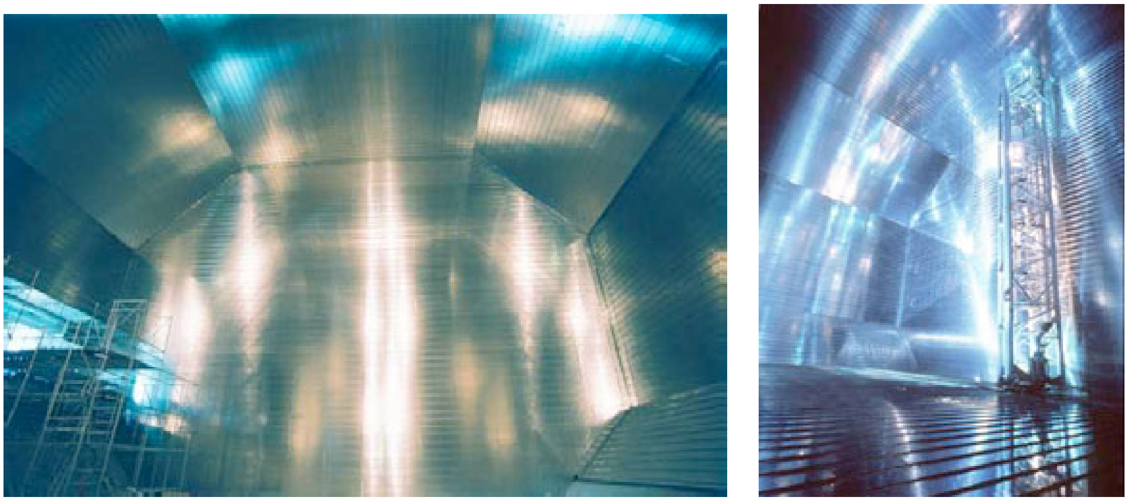

Fig. 3 Invar membrane being installed in ships that are now in service

Two companies hold patents on similar membrane designs, Gaz Transport and Technigaz. With their merger into a single company, GTT, a new design has evolved, patent name CS1 as shown in Figure 4, that combines the best properties of each company's approach. The inner membrane of Invar is retained (but now corrugated in the corners), while Triplex, a material composed of fiberglass and aluminum that is more flexible than Invar is used for the second membrane, while reinforced polyurethane insulation replaces the Perlite. The original and the CS1 designs have undergone extensive finite element analysis and these have been compared to experience with existing ships. It is expected that this new design can be certified against material fatigue failure for 40 years, of operation in the most adverse working conditions, such as those to be found in the North Atlantic.

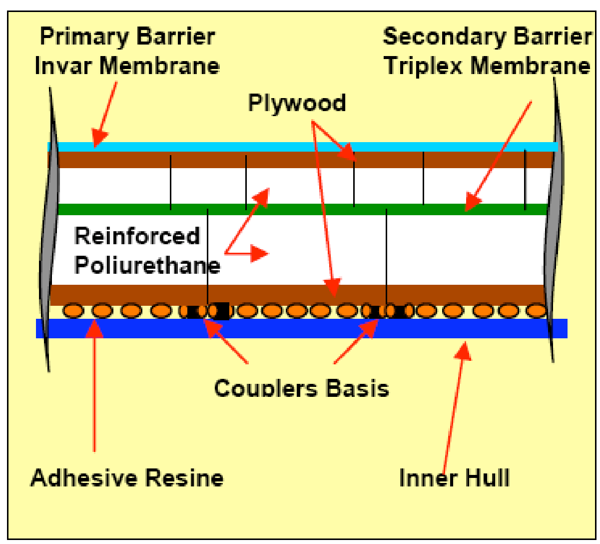

Fig. 4 GTT System CS1 fundamentals

IV. LArTPC Membrane Style Cryostat

The ES&H requirements for a land based LNG tank, or a LNG tanker are harder to satisfy than for the same vessels carrying liquid Argon. A ship carrying LNG can safely sail rough seas, and then unload its cargo in a port near populated areas. I will assume, therefore, that a LArTPC tank built with the same principles to carry a similar amount of liquid (now Argon) can be engineered for safe operation in a deep underground location.

The design of a ship incorporates aspects that would be unnecessary for a land based system. The double hull is designed to fill with ballast water as the cargo is unloaded, and to protect the inner hull in the event of a grounding or a minor collision. Also, the cargo is broken up into 4 or 5 separate compartments because the ship must be balanced at all times, e.g., during loading and unloading of cargo. There doesn't seem to be any safety reasons for the compartments, except that during a return voyage the ship could remain afloat if one of the empty compartments filled with water. One clear difference is that Argon is nearly three times as heavy as natural gas so that stronger versions of the insulation packaging will have to be developed. An engineering study of the membrane approach must be done to determine how it can be safely simplified and strengthened to carry liquid Argon.

Another important engineering issue is the role of the cavern walls in supporting the cryostat. Just placing a full ship design into a cavern results in a cavern with a minimum diameter of 42 m, and an Argon cross section of about 800 m^2, as shown on the

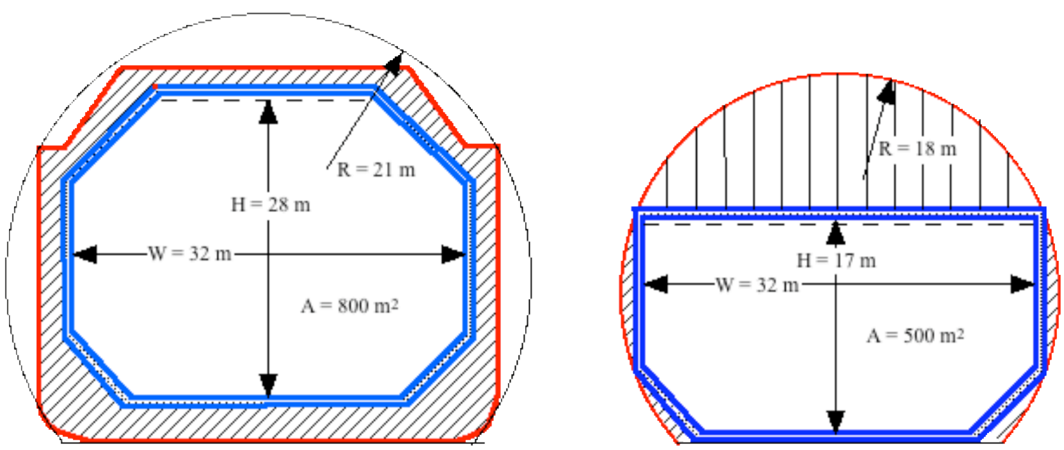

Fig. 5 LArTPC cryostats in a cavern with liquid level indicated by dashed line.

left in Figure 5. The liquid level (dashed line) could not be this high unless the preamplifiers can be located in the liquid, an option that is under investigation. A conservative design would require that the electronics be located outside of the cryostat and the liquid level end at the top of the vertical walls. This lowers the cross sectional area to about 500 m^2. Shown on the right in Figure 5 is a detector using the cavern walls for support that results in diameter of 36 m, and with it a significant savings in costs for steel and excavation. The figure shows the top of the cryostat supported from the cavern roof, however, with cold preamps the entire octagonal tank could fit into this cavern.

Thicker insulation might be needed to keep the rock warm, or a naturally available water flow could warm the outside resulting in an increased refrigeration load.

The costs of this detector can be estimated. The workers will have to trained and must work underground. However, the containers on ships are built from the inside so that their workers also must work in a cave. Steel and nickel prices are rising, as is the cost of energy. A ship 300 m in length that can carry 70 kton of LNG cost < $200 M in 2004. The price must be closer to $250 M today. However, we do not have to build an entire ship, just the inner hull and the insulated Invar tanks. My estimate for the cost of a tank for 100 kton of liquid Argon (140 m long, 70,000 m^3) will cost about 150 M$, not including the excavation costs, which are better estimated by the mining people.

V. Early prototype LArTPC for the 300 ft level.

In the Early Implementation Program (EIP) at the Homestake site[7] there is a proposal to develop a shallow 300 ft level (300L) and a deep 4850 ft level (4850L). The underground laboratories that have been discussed for the EIP are 20 m wide, 15 m high, and 50 m long. To estimate the size of a prototype membrane style cryostat that can fit in this space, I'll assume that the walls can be used for mechanical support and that an outer steel shell can be mounted on the wall. Taking the insulation thickness to be 1 m (double that used on ships) on either side, the Argon volume would be 18 m by 10 m by 50 m long (9,000 m^3) or an Argon mass of 12.6 kTon. In an EIP cavern, a LNG tank of the cylinder type discussed earlier would hold a maximum of 3.5 kT.

VI. Conclusion

It does appear that an ~ 12 kTon prototype LArTPC could be built with Invar membrane technology in an EIP cavern. Realistic engineering will undoubtedly reduce the capacity of this detector. On the other hand, the cavern size of the EIP is very conservative. Studies indicate that caverns of the size necessary to hold 100 kTon of liquid Argon in a deep underground location are possible.

Further studies are needed understand the engineering consequences of the membrane technology. This paper discussed only the tank design. It did not investigate the feasibility of signal towers or how to implement the wire chamber supports, though a number of solutions immediately come to mind,

VII. References

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